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Antarctic Geology

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Antarctica is a very large continent, and for its size relatively little geological work has so far been done there. The area of Antarctica is approximately $5\frac{1}{2}$ million square miles, or about twice that of the United States of America; the Graham Land peninsula is almost the same size as England and Wales. Much of the surface of the continent is relatively unknown and there are still vast areas which have never been seen and remain unexplored. In this respect Antarctica is a new continent; it was only discovered as recently as 1820 by an Englishman, Edward Bransfield.

In the past six years two major undertakings have greatly increased the topographical and geological knowledge of Antarctica. The first important contribution resulted from the scientific work done before and during the first crossing of the continent by the Commonwealth Trans-Antarctic Expedition. The second was the 18-month period of the International Geophysical Year in 1957 and 1958, and its successor, International Geophysical Co-operation, in 1959. 57 scientific stations were specially set up in Antarctica by the 12 participating nations. Numerous scientific disciplines were studied on a synoptic basis, but unfortunately topographic survey and geology were excluded from the I.G.Y. research programme. However, since that time the importance of these aspects of scientific exploration has been fully appreciated and there have been great advances both in survey and geology.

The physiography of Antarctica is interesting, since the continent lies almost entirely within the Antarctic Circle; its most northerly point, at the tip of Graham Land, reaches latitude 63°S . to the south of South America. The central core of Graham Land is a high plateau rising to 6,000–7,000 feet above sea-level, with sheer scarps descending to sea-level on its western and eastern sides. The greater part of Antarctica is covered by a thick ice sheet which is pierced by high mountain ranges and occasional groups of rocky nunataks in certain areas. In many places along the fringe of the continent there is a low ice shelf

which projects from the ice sheet at a height of about 150–200 feet above sea-level. This presents the surveyors with a problem because the continent has no static margin; the ice shelf advances seawards in the winter and breaks back during the following summer.

One of the most fascinating parts of Antarctica is the northern tip of Graham Land, which is as rich in stratigraphical evidence as it is in remarkable glaciers and text-book examples of glacial topography. Many of the mountains along the west coast of Graham Land rise to a height of 5,000–6,000 feet but some of the peaks on the offshore islands, such as Mount Français, reach 9,500 feet. Much of this coastline is protected by an ice cliff, often 150 feet high, thus rendering it almost impregnable in many places without the aid of helicopters. The "tumbled" glaciers of the west coast are virtually impassable and, therefore, the coastal scientific stations are often precariously sited on tiny promontories between towering ice cliffs or on offshore islands; these sites are frequently the only places for many miles from which a foothold can be gained on the peninsula for scientific work. Behind the coastal cliffs the mountains of the hinterland are dangerous and usually unclimbable because of the frost-shattered rock. Equally treacherous are the narrow channels between the offshore islands, the coastal shoals and the glaciers; the coastal areas of Antarctica, as typified by western Graham Land, present a beautiful but most inhospitable scene.

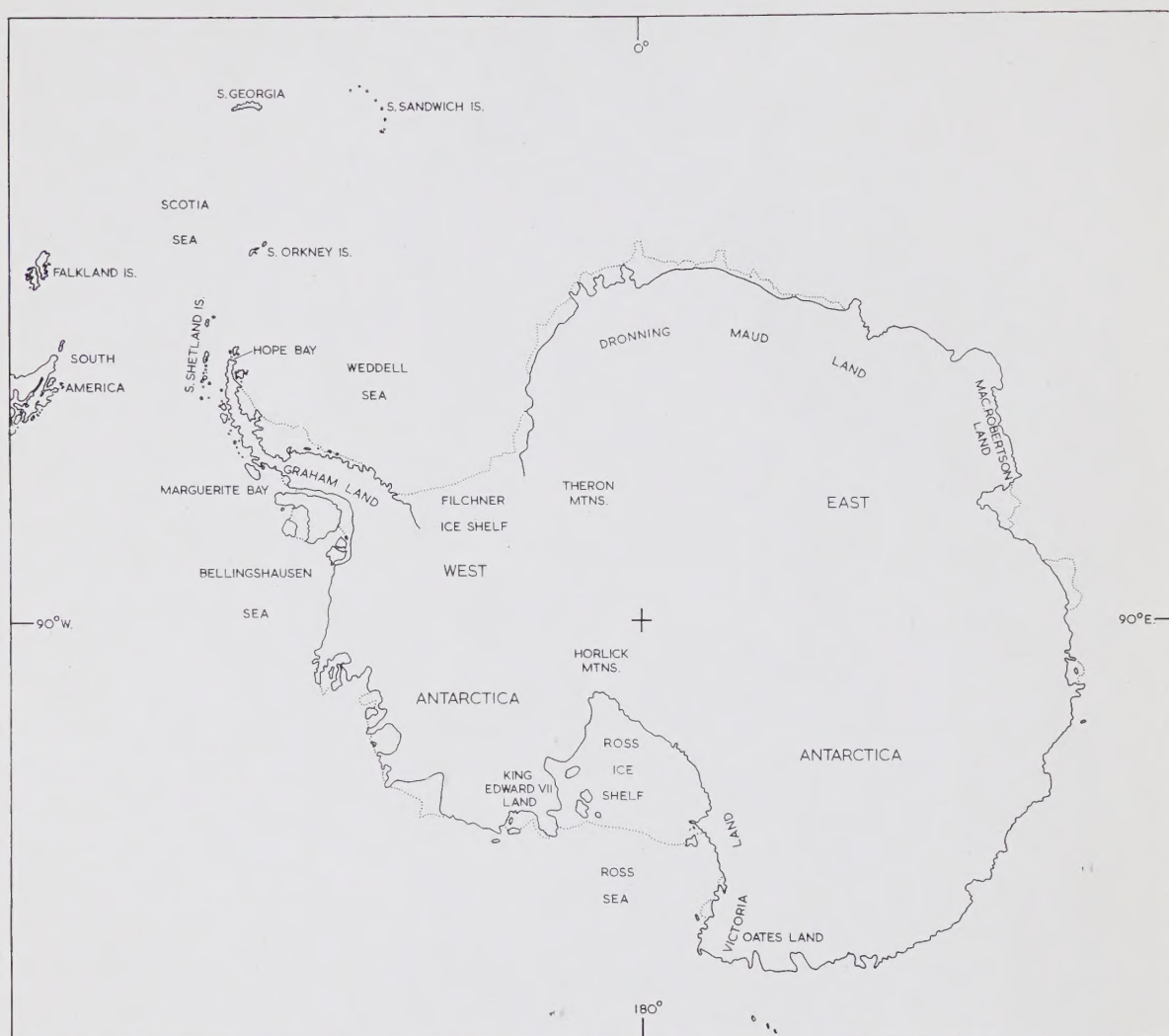
The central Antarctic Ice Sheet is no more inviting—it is a monotonous region rising up to 10,000–14,000 feet above sea-level, but across which "Sno-cats" and tractors can travel with relative ease. Only isolated snow-covered mountains and deep crevasses break the miles of nothingness; and near the fringe of the ice sheet vast rivers of ice, like the Beardmore Glacier, creep steadily between the stark rocky ridges, draining the ice sheet to the ice shelf below. On the central plateau both navigation and exploration are difficult, and it may well be some years before the true configuration of the ice surface

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and the sub-ice topography become known completely. However, it is now known that the fundamental structure of the continent is that of a heavily dissected, undulating rock basement over which an ice carapace flows outwards, forming in places the peripheral ice shelf.

In the Antarctic the topographical surveyor employs many of the accepted instruments and techniques for his work, but the geologist's methods are often very different. He uses the stratigraphical succession of an area and its interpretation to deduce the physical features of the country during the past: the distribution of land and sea. In fact, wherever possible, he adopts the techniques of palaeogeography by interpreting the nature of the sediments to

determine the respective positions of shorelines, lakes, deserts and mountains at various times in the past. To assist in this interpretation, there may be reference to palaeoclimatological evidence. The distribution of fossil plants is often important once their optimum climatic environment and range has been established. For instance, modern relatives of the Tertiary plants still inhabit certain climatic zones of the world, and this information can be used to interpret the Tertiary climatic zones. Similar principles can also be applied to some forms of invertebrate marine life: studies on the gastropods, lamellibranchs and brachiopods have shown that their respective shell thicknesses are directly related to the temperature and salinity of the sea in which that organism lived.



Mount Flora at Hope Bay, north-east Graham Land, where well-preserved fossil plants of Middle Jurassic age occur in black fresh-water shales. (*British Antarctic Survey photograph.*)

Equally interesting are the recent studies of palaeomagnetism and the useful information they have yielded. In the past, when a sediment was deposited, each small magnetic particle was stamped with the polarity of the Earth's magnetic field of that time. Likewise, all crystals of magnetic minerals in igneous rocks received the imprint of the existing Earth's magnetic field. By taking samples from rocks of different periods during the Earth's history it is not difficult to analyse statistically their remanent magnetism and thus determine the position of the Earth's magnetic field at the time the rock was emplaced. Unfortunately, by the application of this technique it is only possible to fix the former latitudes of the rock samples and not their original meridional positions. This method then has a direct link with the palaeoclimatic interpretations mentioned earlier.

Over the past 19 years several thousand square miles of Graham Land have been mapped geologically by the British Antarctic Survey and many interesting finds have been made. This work has been directed not only to the elucidation of the geological record of Graham Land but also to the unravelling of the palaeogeography, the palaeoclimatic and environmental history of the region, and its relation to Antarctica as a continental landmass. The very presence of fossil plant remains is a clear indication that the climatic environment in which they flourished was somewhat different from that existing now in Antarctica. One of the most important examples is the Hope Bay area of northern Graham Land, where well-preserved plants of

Middle Jurassic age have been found in the black fresh-water shales of Mount Flora. Fresh specimens of these fern-like plants are a rich golden colour, since many of them are preserved in iron pyrites. At that time these plants grew on the edge of a huge lake, inhabited by small fish, whose vertebrae and teeth have been found, and fresh-water gastropods. The picture has recently been completed by the interesting discovery of perfectly preserved wing-cases of aquatic beetles that lived and crawled among the ferns bordering the lake. From this sort of palaeontological and stratigraphical information it is possible to reconstruct with reasonable precision the climate and environment in which these animals lived 150 million years ago.

The later history of this area is less accurate but in part it can be deduced from the volcanic succession that overlies the black plant-bearing shales; a series of volcanic explosions showered hot ash over the whole area and destroyed the luxuriant subtropical flora. Not far away, to the south of Hope Bay, a complete forest was inundated by the hot ashes from these same eruptions and burnt *in situ*. This situation was no doubt similar to that responsible for the recent destruction of forests on the slopes of the volcanoes of the western seaboard of the United States.

From this sort of evidence, in association with that provided by other studies, it has been possible to deduce that 150 million years ago this part of Antarctica occupied a position in about latitude 40°S. and was not in its present position of

latitude 63°S. Not only the sediments but also the volcanic rocks, which can be traced far southward into the Marguerite Bay area of southwest Graham Land, support these conclusions.

By the careful interpretation of the stratigraphy and the geological mapping the configuration of the old land surfaces of Graham Land can be reconstructed from as long ago as 600 million years. For more recent times there are other means of detecting changes in climate and landscape: recent deglaciation is indicated by the remnants of old U-shaped glacial valleys, moraines and the presence of old granite erratics perched 1,400 feet above the present ice level on the tops of volcanic nunataks; they could only have been lodged there by moving ice.

The principles of palaeogeography are constantly being applied to the available information and this has been particularly successful in the case of Deception Island in the South Shetland Islands. This horseshoe-shaped island is a most interesting remnant of the volcanic episode that swept the South Shetland Islands group in late Tertiary to Recent times. Its exact history and topographic configuration has been reconstructed from 10–15 million years ago: subsequent to the eruption of four adjacent primitive volcanoes the central part of the island collapsed, leaving three separate islands; a second series of eruptions along the ring fracture filled the gaps and initiated the island's present topography; two further eruptive cycles, the last of which was as late as 1842 (recorded by observers on passing ships), completed the island's volcanic history. Today, only steam and sulphurous fumaroles, an interesting lake, numerous slag-bounded craters and ice-covered morainic features bear witness to the turbulent past of Deception Island.

Turning now to the larger stratigraphical picture of Antarctica: from the viewpoint of the geologist the continent can be subdivided into two major geological provinces which almost coincide with the two main topographic divisions of West and East Antarctica. This geological sub-division of Antarctica is based on detailed stratigraphical studies which are now to be considered more critically.

In East Antarctica there are six geologically important and well-known areas: Victoria Land, Oates Land, MacRobertson Land, Dronning Maud Land, the Theron Mountains and Whichaway Nunataks, and the central Horlick Mountains.

The well-known stratigraphy of Victoria Land represents the typical succession of East Antarctica. There is a basement of Precambrian crystalline rocks, followed by Cambrian *Archæocyathus* limestones (until recently known only from erratics) and late Devonian sediments containing plant remains. The great thickness of terrestrial sediments which constitute the Beacon System (late Palaeozoic-Mesozoic) is intruded by

thick dolerite sheets and caps the whole area. After a long time interval the McMurdo Volcanics were extruded in the late Tertiary to Recent. In Oates Land there is a similar succession: the Basement, Devonian plant-bearing sediments, the Beacon System and finally the Quaternary Volcanics. In MacRobertson Land the southern "coal measures" appear at the base of the Beacon System. They are Lower Permian in age and are therefore younger than the Carboniferous "coal measures" of the Northern Hemisphere. A similar succession to that of MacRobertson Land is present in Dronning Maud Land, but in the Theron Mountains area the Basement Complex, the older slate-quartzite beds and *Archæocyathus* limestones (as erratics) and the Beacon System with the basal "coal measures" appear again. In the central Horlick Mountains, only 5° of latitude from the South Pole, the geological succession is closely akin to that of Victoria Land but with one exciting exception: unconformably overlying both the marine fossiliferous Lower Devonian sediments and the Basement Complex is the Buckeye Tillite, a fossil morainic deposit resulting from the great Permo-Carboniferous glaciation of Antarctica. It is also interesting to note that an abundance of fossil plant material and numerous coal seams have been discovered in the Lower Permian part of the Beacon System in this same area.

A comparison of this recurrent pre-Jurassic stratigraphic pattern of East Antarctica with the geological succession of South Africa shows numerous points of identity: the Basement Complex, the marine Lower Devonian beds, the mid-Devonian plant-bearing beds, the Permo-Carboniferous tillites, the Lower Permian "coal measures" with the associated fossil flora and woods, the upper beds of the Beacon System (the Gondwana System of other Southern continents) and the Lower Jurassic Ferrar Dolerites (Karoo Dolerites). In Brazil, Uruguay, Argentina, the Falkland Islands, India and eastern Australia there are also stratigraphic similarities, and therefore it would be fair to assume that the geological development in each of these areas was concurrent, that these areas were in closer proximity in the past, and that similar environmental conditions existed at various times in the pre-Jurassic. It is, however, interesting to note that, in contrast with the above comparison, there are no similarities between East Antarctica and the other southern continents in their post-Jurassic histories.

In West Antarctica the geological situation is totally distinct from that of East Antarctica. Although there is a Basement Complex which is probably of a different (or younger) age than that of East Antarctica, the Palaeozoic, Mesozoic and Tertiary history is closely akin to that of the West Patagonian Cordillera. In West Antarctica two well-known geological areas form the basis for comparative studies: the Scotia Arc and Graham Land peninsula, and King Edward VII Land.

A submarine ridge, which is known as the Scotia Arc and comprises South Georgia, the South Sandwich Islands, the South Orkney Islands, and the South Shetland Islands, links the southern tip of South America to Graham Land. Metamorphic rocks of the Basement Complex are present only in the South Orkney Islands, the north-east part of the South Shetland Islands and in south-western Graham Land, but in several localities there are intrusive and volcanic rocks of early Palaeozoic age. Carboniferous geosynclinal sediments of the Trinity Peninsula Series occur both in north-east Graham Land and at isolated localities along the flanks of the peninsula, extending into the Sentinel Mountains in the heart of West Antarctica. In isolated parts of northern Graham Land fresh-water lakes were present in the Middle Jurassic and in these were deposited the fern-like plants referred to earlier. In the Upper Jurassic there were extensive volcanic eruptions, and interbedded lavas and ashes at least 10,000 feet thick have been recorded in some localities in western Graham Land. Rejuvenation of the Andean geosyncline in the Cretaceous gave rise to sedimentation off north-east Graham Land, where an abundant well-preserved fauna has been found. Towards the close of the Cretaceous, Graham Land, as it appears today, was formed by the emplacement of gabbro, quartz-diorite and granite batholiths of the Andean Intrusive Suite. Although there was local sedimentation in the early Tertiary, this was mainly a period of further volcanic eruptions in north-east Graham Land and the South Shetland Islands.

In King Edward VII Land the geological record is indeed similar to that of Graham Land though somewhat incomplete. Only the Carboniferous geosynclinal sediments, the Andean Intrusive Suite and the mid-Miocene volcanic rocks are represented there.

Geologically, Graham Land is a mirror image of Patagonia; in both regions there is essentially the same stratigraphic succession (the same sequence of geological events), and in Patagonia there is abundant evidence of the two geosynclines represented in Graham Land. However, there is one striking point: the Andean Intrusive Suite of Patagonia is older than that of Graham Land, indicating that in the South American Andes, the Scotia Arc and the Antarcticandes of Graham Land intrusion was not contemporaneous as was previously thought, but began in Patagonia and migrated southwards into Graham Land.

The initial part of the geological study of any area is mostly routine work—mapping, the correlation of stratigraphy and the investigation of structure; the interpretation of the geological record in terms of environmental conditions—climatic and geographical—is probably more interesting. As far as Antarctica is concerned, the available evidence on which to base interpretation is still meagre, but even so it is now possible to trace the geological history of this continent over the past 600 million years.

Underlying the whole continent is a basement of highly metamorphosed crystalline rocks of Precambrian age (more than 600 million years old). About 500 million years ago a large part of the landmass was inundated by the sea which did not withdraw until late Devonian times. During the Permo-Carboniferous Antarctica suffered sudden refrigeration, which resulted in the great glaciation so well-known from the tillites of South America, South Africa, Australia and India. The continent was denuded of its surface material by the outward-flowing ice sheet which carried it to all parts of the Southern Hemisphere. So widespread and active was the ice sheet that very little trace of its existence is to be found today in modern Antarctica. It is probable that some of this morainic debris was deposited together with the greywacke sediments in the great Andean geosyncline of West Antarctica which had formed just before this time.

Following the recession of glaciation in East Antarctica, a great inland basin developed. In this basin were deposited the terrestrial sediments which carry the Lower Permian "coal measures," now recognized to be the largest unexplored coal-field in the world. The early Mesozoic heralded the onset of desiccation which was closely followed, in Jurassic times, by the most disruptive though constructive period in the continent's history. While thick dolerite sills intruded the "coal measures" of East Antarctica and small-scale volcanic eruptions occurred locally, the Graham Land region of West Antarctica became a scene of total desolation with widespread eruptions and the complete destruction of the once-flourishing flora. To the south-west of Graham Land even the marine fauna was destroyed and buried by the vast quantity of volcanic ash showering into the sea from the land volcanoes. The early Tertiary period (70–50 million years ago) shaped Graham Land and the South Shetland Islands as they are today; igneous intrusions, minor sedimentation and local volcanic eruptions all played their part. It seems that there was a long period of inactivity in the geological history of East Antarctica between the Jurassic and the Pliocene, when the great volcanoes such as Mount Erebus began erupting. A return to total refrigeration in the Pleistocene completes the oscillation of climate in Antarctica.

A comparison of the respective structures and tectonic styles of East and West Antarctica reveals striking dissimilarities. Although the Basement Complex and Lower Palaeozoic rocks of the continent have undergone the same regional metamorphic history, it is clear that the tectonics of East Antarctica are relatively simple and are those associated with a stable continental platform. The widespread terrestrial deposits of the Beacon System are invariably near-horizontal and this is even more emphasized by the Ferrar Dolerite intrusions. Faulting is probably of late Tertiary age and with which the late volcanic eruptions were associated.

In contrast, West Antarctica has had a more varied tectonic history, which is associated with the emergence of the Andean geosynclinal sediments in near pre-Jurassic times. These sediments were acutely folded by an orogeny related to the formation of the "primitive" Scotia Arc. Further mild folding occurred in Graham Land with the emplacement of the Andean Intrusive Suite in the late Cretaceous to early Tertiary. Associated block-faulting has in part been responsible for much of the present topography of West Antarctica and the plateau of the Graham Land peninsula. Rejuvenation of faulting along earlier lines in the late Tertiary was probably related to the onset of the last phase of volcanism.

As it is today Antarctica is covered by a huge ice sheet through which very little rock is exposed. To the geologist this presents a challenge which requires special techniques, including gravity and magnetic surveys, and seismic shooting. By these means it is possible to determine exactly the configuration and depth of the bedrock beneath the snow and ice, and whether the ice rests on water or on rock. In recent years the Americans and Russians have made seismic traverses over much of East Antarctica. It has been established that, while the ice surface at the South Pole is in fact about 10,000 feet above sea-level, the bedrock itself is only about 800 feet above the sea. Surveys in West Antarctica indicate that, although the highest points rise to 8,000 feet above sea-level, there are large areas, such as the Filchner and Ross Ice Shelves, where the bedrock lies below sea-level.

This form of probing beneath the ice sheet has led to at least one great discovery. The idea that a sub-ice channel links the Ross and Weddell Seas is quite fallacious; instead, it has been proved that there is a channel about 8,000 feet deep, almost joining the Ross and Bellingshausen Seas. This is probably the most significant discovery in subglacial investigation. It means that, if the Antarctic Ice Sheet were to melt, only the long peninsula of Graham Land, part of the bulbous mass of East Antarctica and a few small islands would remain, and the total area of Antarctica above sea-level would be reduced to almost half its present size. Since deglaciation has been proceeding for at least 2,500 years, it seems that Antarctica is a "shrinking continent".

Thus far, the salient features of the geology of Antarctica have been discussed. But, is it in fact correct to relate the geological history of Antarctica to the present distribution of the southern continents? Surely not, because there is now available ample evidence to suggest that the southern continents were in closer proximity to each other prior to 70 million years ago. Until recently Antarctica was the unknown fragment of the geological jig-saw puzzle, but now that the history of this continent has been partially unravelled it is clear that East Antarctica is the primitive continental shield with Gondwana affinities and that West Antarctica, including the Antarcticandes, is the southern counterpart of the Andes, or a younger part of the continent welded on to the continental shield at a relatively late stage in its history.



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